

# $K_S \rightarrow \pi^+ \pi^- l^+ l^-$ and other interesting kaon decays

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**Workshop on Rare Strange Decays at LHCb, CERN, 6th December 2013**

- $K \rightarrow \pi\pi\gamma$ -decays,  $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$ ,  $K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-$  work in collaboration with L. Cappiello, O.Cata, M. Sokoloff
- $K_S \rightarrow \pi^0 \mu^+ \mu^-$ ,  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  and related channels

$$K(p_K) \rightarrow \pi(p_1)\pi(p_2)\gamma(q)$$

- Lorentz + gauge invariance  $\Rightarrow$  Electric ( $E$ ) and Magnetic ( $M$ ) amplitude

$$A(K \rightarrow \pi\pi\gamma) = F^{\mu\nu} [E \partial_\mu K \partial_\nu \pi + M \varepsilon_{\mu\nu\rho\sigma} \partial^\rho K \partial^\sigma \pi]$$

- Unpolarized photons

$$\frac{d^2\Gamma}{dz_1 dz_2} \sim |E|^2 + |M|^2$$

$$|E^2| = |E_{IB}|^2 + 2\text{Re}(E_{IB}^* E_D) + |E_D|^2$$

↓

$$\text{Low Theorem} \Rightarrow E_{IB} \sim \frac{1}{E_\gamma^*} + c \quad E_D, M \text{ chiral}$$

tests

We need **FIGHT**  $DE/IB \sim 10^{-3}$

	<i>IB</i>	<i>DE<sub>exp</sub></i>	
$K_S \rightarrow \pi^+ \pi^- \gamma$	$10^{-3}$	$< 9 \cdot 10^{-5}$	<i>E1</i>
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	$10^{-4}$ <i>(<math>\Delta I = \frac{3}{2}</math>)</i>	$(0.6 \pm 0.04) 10^{-5}$ <i>PDG</i>	<i>M1, E1</i>
$K_L \rightarrow \pi^+ \pi^- \gamma$	$10^{-5}$ <i>(CPV)</i>	$(2.84 \pm 0.11) 10^{-5}$ <i>KTeV</i>	<i>M1,</i> <i>VMD</i>

**CPV** is **only** from IB  $K_L$  (also **measured** in  $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ )

**BUT** IB suppressed in  $K^+$  and  $K_L$ .

$$K^+ \rightarrow \pi^+ \pi^0 \gamma$$

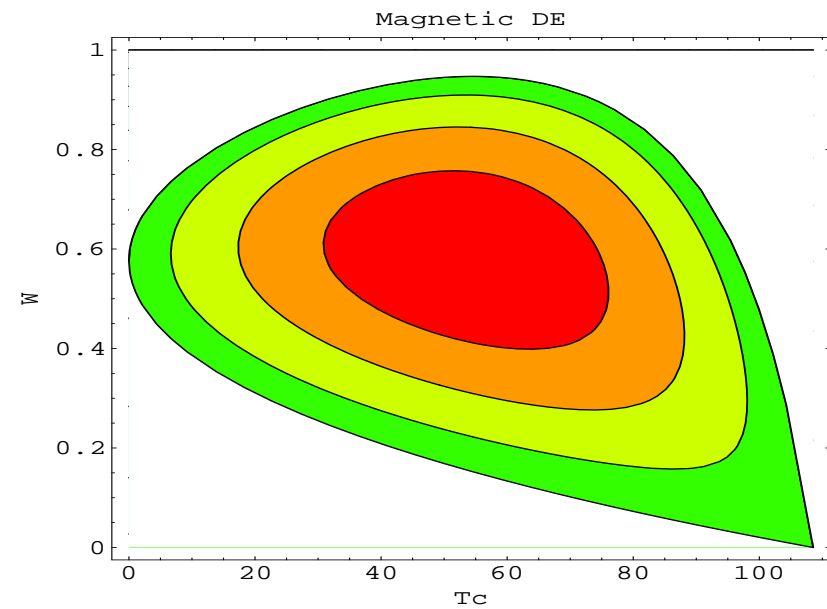
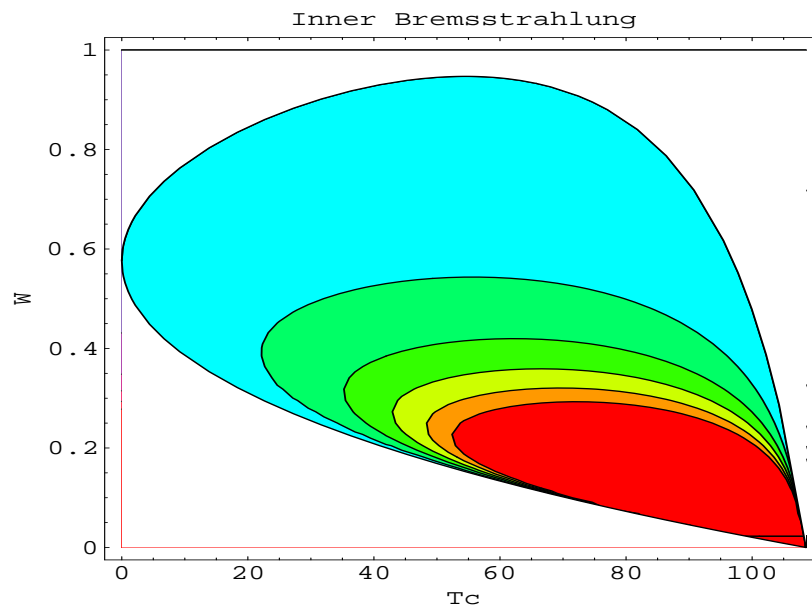
$$A(K \rightarrow \pi \pi \gamma) = F^{\mu\nu} [E \partial_\mu K \partial_\nu \pi + M \varepsilon_{\mu\nu\rho\sigma} \partial^\rho K \partial^\sigma \pi]$$

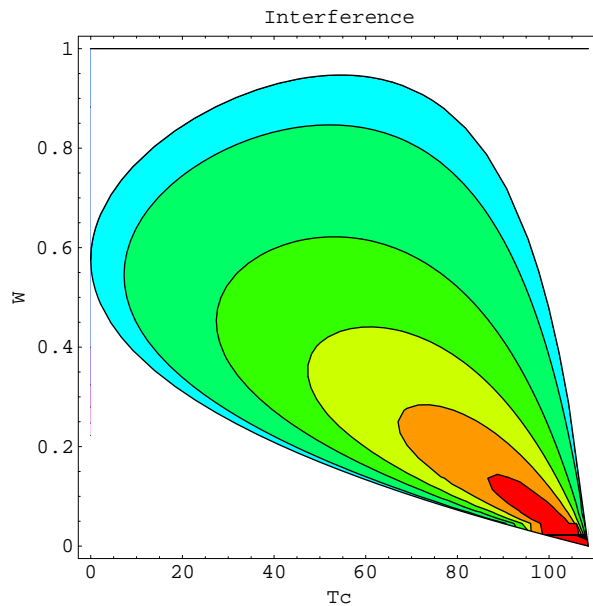
$E1$  and  $M1$  are measured with Dalitz plot

$$\frac{\partial^2 \Gamma}{\partial T_c^* \partial W^2} = \frac{\partial^2 \Gamma_{IB}}{\partial T_c^* \partial W^2} \left[ 1 + \frac{m_{\pi^+}^2}{m_K^2} 2 \operatorname{Re} \left( \frac{E1}{eA} \right) W^2 + \frac{m_{\pi^+}^4}{m_K^2} \left( \left| \frac{E1}{eA} \right|^2 + \left| \frac{M1}{eA} \right|^2 \right) W^4 \right]$$

$$W^2 = (q \cdot p_K)(q \cdot p_+) / (m_\pi^2 m_K^2)$$

$$A = A(K^+ \rightarrow \pi^+ \pi^0)$$

$K^+ \rightarrow \pi^+ \pi^0 \gamma$   $W - T_c$  Dalitz plotIntegrating over  $T_c$  deviations from IB measured

**CP asymmetry**  $K^+ \rightarrow \pi^+ \pi^0 \gamma$ 

Dalitz plot analysis crucial

$$\text{SM} \leq \mathcal{O}(10^{-5})$$

Paver et al.

$$\text{NP} \leq \mathcal{O}(10^{-4})$$

Colangelo et al.

$$\text{NA48/2} \quad < 1.5 \cdot 10^{-3} \quad \text{at} \quad 90\% \quad \text{CL}$$

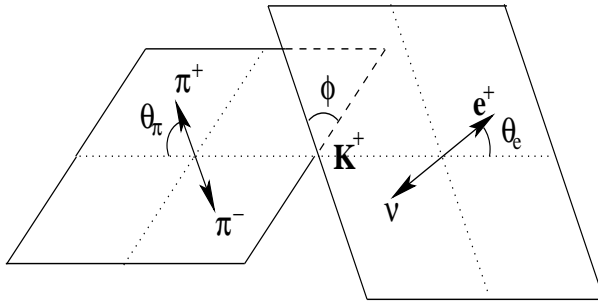
**BUT NOT** in the interesting interf. kin. region (statistics)

$K_{l4}$  and  $\pi\pi$  strong phases  $\delta_I^l(s)$ 

Cabibbo Maksymowicz

$$\frac{G_F}{\sqrt{2}} V_{us} \bar{e} \gamma^\mu (1 - \gamma^5) \nu H_\mu(p_1, p_2, q)$$

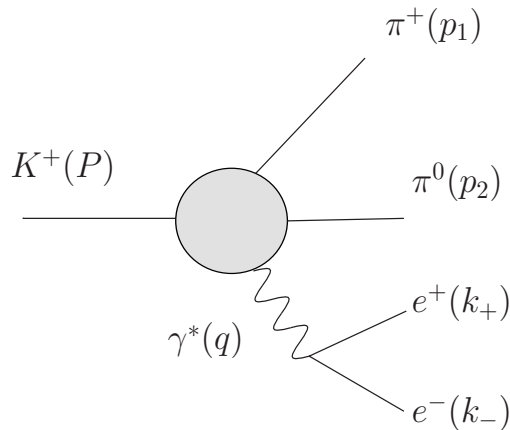
$$H^\mu = F_1 p_1^\mu + F_2 p_2^\mu + F_3 \varepsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} q_\beta. \quad F_i(s) = f_i(s) e^{i\delta_0^0(s)} + ..$$



- crucial to measure  $\sin \delta \implies$  interf  $F_3$
- Look angular plane asymmetry

$$K_L \rightarrow \pi^+ \pi^- \gamma^* \rightarrow \pi^+ \pi^- e^+ e^-$$

Sehgal et al; Savage, Wise et al



- $\mathcal{M}_{LD} = \frac{e}{q^2} \bar{e} \gamma^\mu (1 - \gamma^5) e H_\mu$
- $H^\mu = F_1 p_1^\mu + F_2 p_2^\mu + F_3 \varepsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} q_\beta$
- $F_{1,2} \sim E \quad F_3 \sim M$

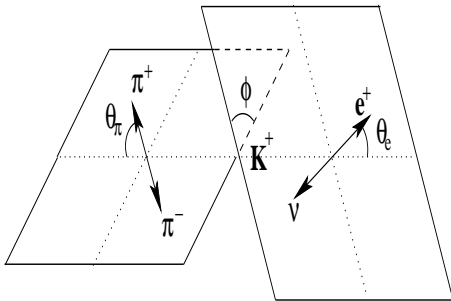
- Interference  $E \quad M$  novel compared to  $K_L \rightarrow \pi^+ \pi^- \gamma$
- $E \quad M$  known from  $K_L \rightarrow \pi^+ \pi^- \gamma$  (IB and DE)



$$K_L \rightarrow \pi^+ \pi^- \gamma^* \rightarrow \pi^+ \pi^- e^+ e^- \quad \theta_\ell, \phi \text{ vs } \theta_\pi$$

$$\begin{aligned} \frac{d^5\Gamma}{dE_\gamma^* dT_c^* dq^2 d\cos\theta_\ell d\phi} &= \mathcal{A}_1 + \mathcal{A}_2 \sin^2 \theta_\ell + \mathcal{A}_3 \sin^2 \theta_\ell \cos^2 \phi \\ &+ \mathcal{A}_4 \sin 2\theta_\ell \cos \phi + \mathcal{A}_5 \sin \theta_\ell \cos \phi + \mathcal{A}_6 \cos \theta_\ell \\ &+ \mathcal{A}_7 \sin \theta_\ell \sin \phi + \mathcal{A}_8 \sin 2\theta_\ell \sin \phi + \mathcal{A}_9 \sin^2 \theta_\ell \sin 2\phi \end{aligned}$$

- $\mathcal{A}_{1,..,4}$  IB,  $\mathcal{A}_{8,9}$ , CPV  $B$ - $M$  interf.
- $\frac{\Re(E_B M^*)}{|E_B|^2 + |M|^2}$  is maximal,  $\sim 0.1$
- $\mathcal{A}_{5,6,7}$  interf. axial leptonic current ,  $\mathcal{A}_P$  SD

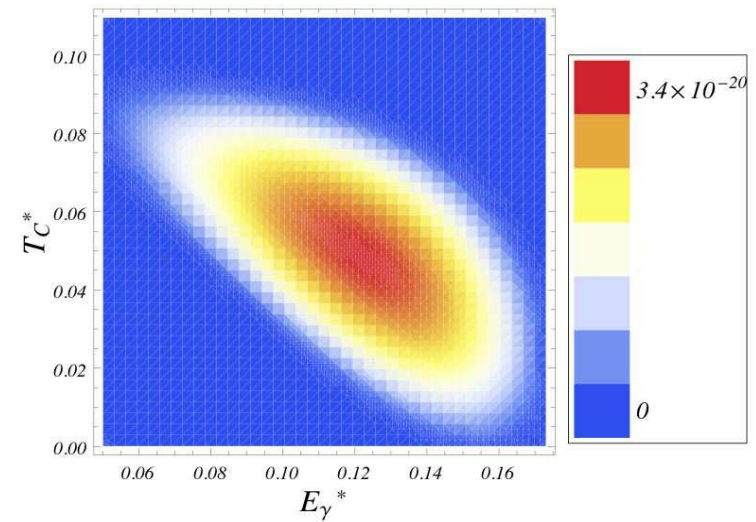
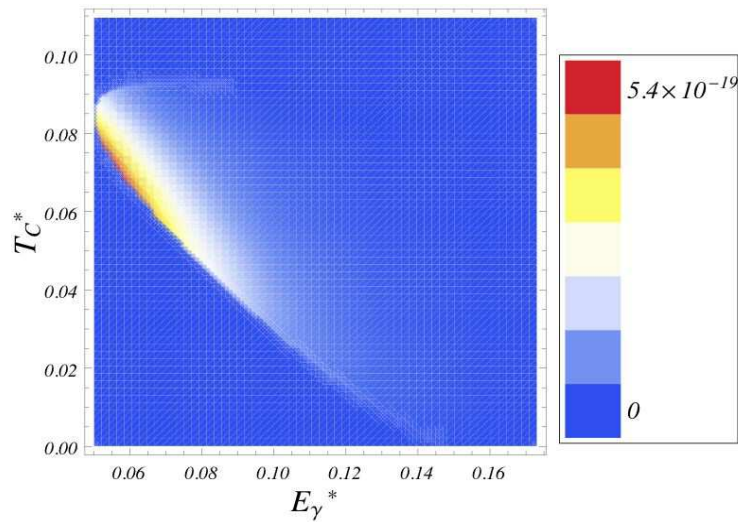


$$K^+ \rightarrow \pi^+ \pi^0 \gamma^* \rightarrow \pi^+ \pi^0 e^+ e^-$$

Cappiello, Cata, G.D. and Gao,

- the asymm. ,  $\frac{\Re(E_B M^*)}{|E_B|^2 + |M|^2}$ , not as lucky  $E_B \gg M$ :
- $B(K^+)_{IB} \sim 3.3 \times 10^{-6} \sim 50 B(K^+)_{M}$
- Short distance info without having simultaneously  $K^+$  and  $K^-$ , asymm. in phase space, ( P-violation) interesting! No  $\epsilon$ -contamination
- interesting Dalitz plots (at fixed  $q^2$ ) to disentangle  $M$  from  $E_B$
- at  $q^2 = 50\text{MeV}$  IB only 10 times larger than DE

$q_c$ (MeV)	B [ $10^{-8}$ ]	B/M	B/E	B/BE	B/BM
$2m_l$	418.27	71	4405	128	208
55	5.62	12	118	38	44
100	0.67	8	30	71	36
140	0.04	9	10	-45	37
180	0.003	12	5	-19	44



$$K_S \rightarrow \pi^+ \pi^- e^+ e^- \text{ and } K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-$$

$$BR(K_S \rightarrow \pi^+ \pi^- e^+ e^-)_B = 4.73 \times 10^{-5}$$

$$BR(K_S \rightarrow \pi^+ \pi^- e^+ e^-)_{BE} = 2.68 \times 10^{-8}$$

$$BR(K_S \rightarrow \pi^+ \pi^- e^+ e^-)_E = 6.82 \times 10^{-11}$$

The branching ratio of the Brehmsstrahlung is very close to the PDG value

$$BR(K_S \rightarrow \pi^+ \pi^- e^+ e^-)_{PDG} = (4.79 \pm 0.15) \times 10^{-5}$$

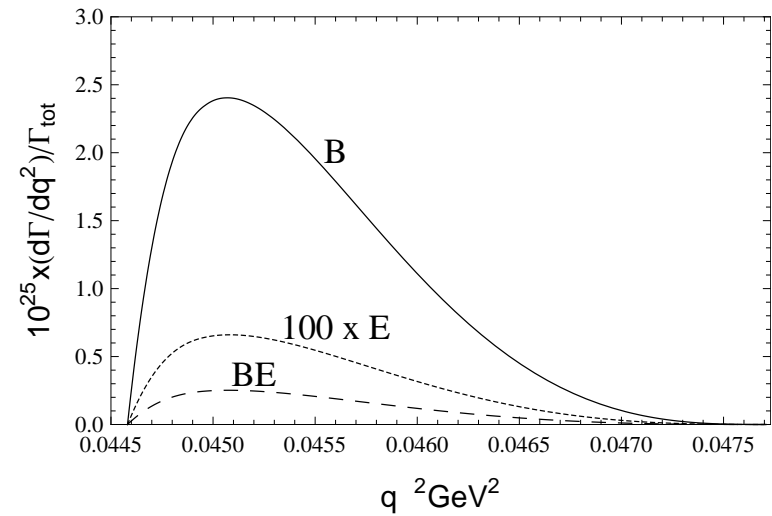
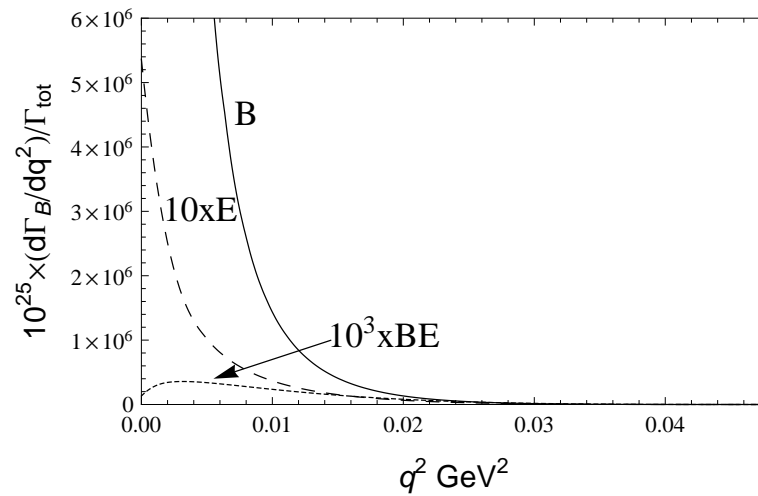
$K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-$  7.15 MeV phase space

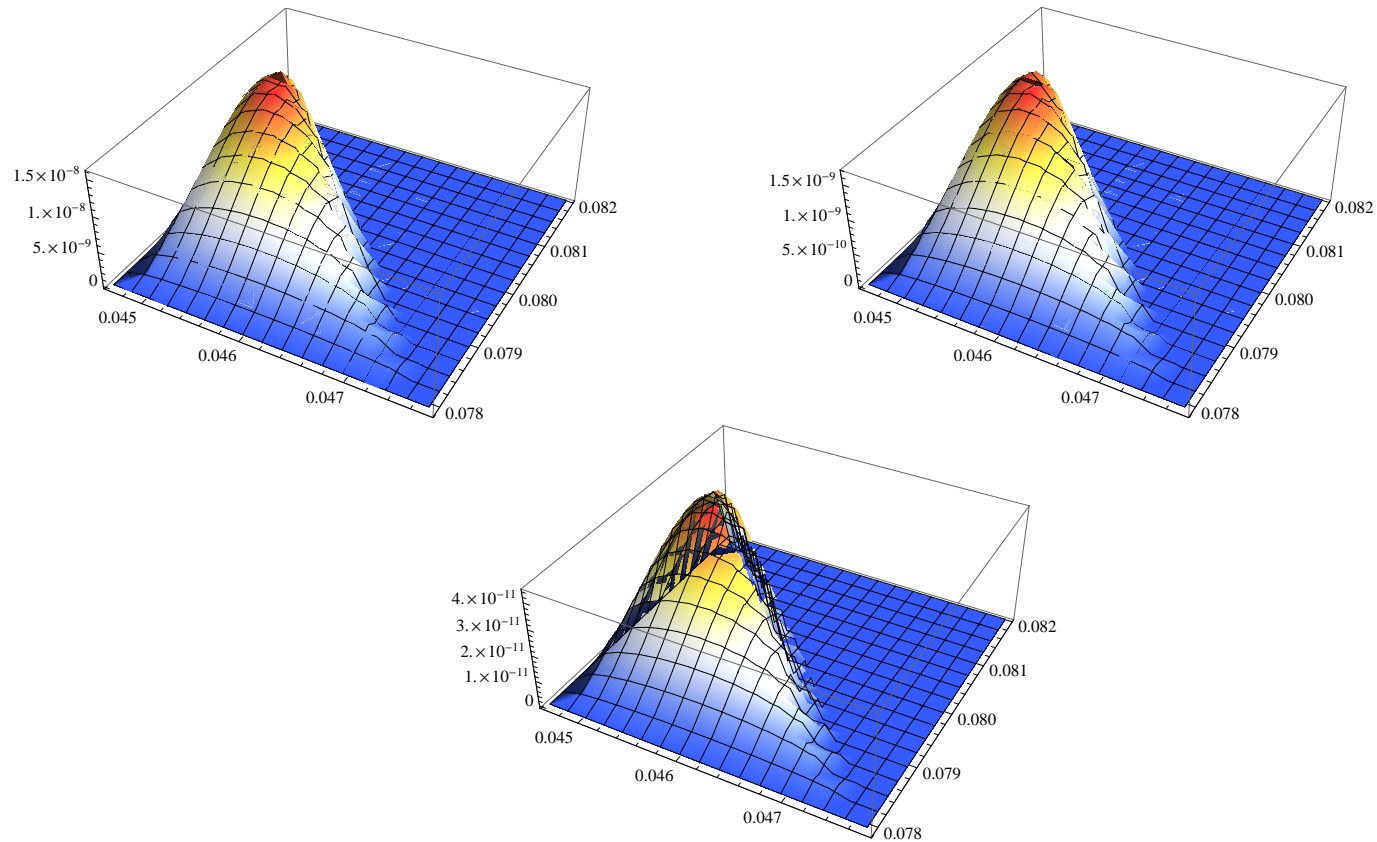
$$BR(K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-)_B = 4.17 \times 10^{-14}$$

$$BR(K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-)_{BE} = 4.40 \times 10^{-15}$$

$$BR(K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-)_E = 1.16 \times 10^{-16}$$

$$K_S \rightarrow \pi^+ \pi^- e^+ e^- \quad \text{and} \quad K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-$$

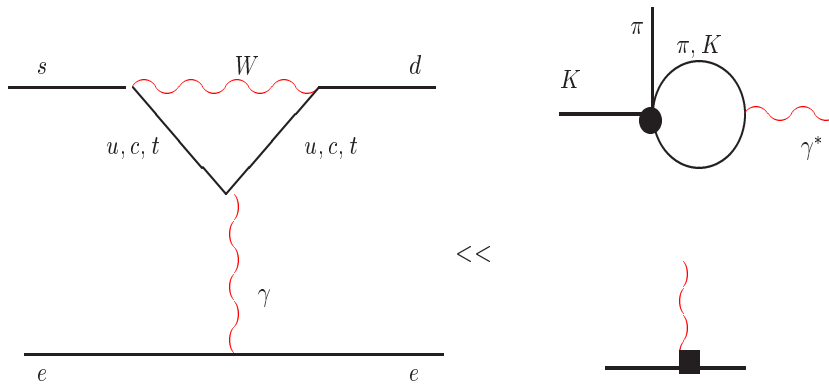


$K_S \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ : **B, interf, DE**

$$K^\pm(K_S) \rightarrow \pi^\pm(\pi^0)l^+l^-$$

- short distance  $\ll$  long distance

LD described by form factor  $W$



$$W^i = G_F m_K^2 (a_i + b_i z) + W_{\pi\pi}^i(z)$$

$$i = \pm, S$$

$$a_i, b_i \sim O(1), \quad z = \frac{q^2}{m_K^2}$$

- Observables  $\Gamma(K^+ \rightarrow \pi^+ e^+ e^-)$ ,  $\Gamma(K^+ \rightarrow \pi^+ \mu \bar{\mu})$ , slopes

- $a_i \sim O(p^4)$

Ecker, Pich, de Rafael

- $b_i \sim O(p^6)$

G.D., Ecker, Isidori, Portoles

- $a_+, b_+$  in general not related to  $a_S, b_S$

- Expt. E865 and NA48

$$K^+ \rightarrow \pi^+ e^+ e^- : a_+ = -0.586 \pm 0.010 \quad b_+ = -0.655 \pm 0.044$$

$$\text{confirmed NA48 } K^+ \rightarrow \pi^+ \mu \bar{\mu} \quad a_+ = -0.575 \pm 0.039 \quad b_+ = -0.813 \pm 0.145$$

Problems:  $\frac{a_i}{p^4}$   $\frac{b_i}{p^6}$  same phenomenological size  
different theoretical order

Probably explained by large VMD. Then we can just parameterize

$$\text{Br}(K_S \rightarrow \pi^0 e^+ e^-) = 4.6 \times 10^{-9} a_S^2$$

not predicted but dynamically interesting:  $a_S \sim \mathcal{O}(1)$  (?): NA48



$K_S \rightarrow \pi^0 e^+ e^-$  at NA48/1 Collaboration at CERN

- 7 events observed (with 0.15 expected background events)

$$B(K_S \rightarrow \pi^0 e^+ e^-)_{m_{ee} > 165 \text{ MeV}} = (3.0_{-1.2}^{+1.5} \pm 0.2) \times 10^{-9}$$

$$|a_S| = 1.08_{-0.21}^{+0.26}$$

Using Vector matrix element and form factor equal to 1

$$B(K_S \rightarrow \pi^0 e^+ e^-) = (5.8_{-2.4}^{+2.9}) \times 10^{-9}$$

- 6 events observed in  $K_S \rightarrow \pi^0 \mu^+ \mu^-$ :

$$|a_S| = 1.54_{-0.37}^{+0.40}$$

- The large slope for  $K^+ \rightarrow \pi^+ e^+ e^-$  calls for large VMD
- $K^+ \rightarrow \pi^+ e^+ e^-$  receives substantial  $\pi\pi$ -loop, **contrary** to  $K_S \rightarrow \pi^0 e^+ e^-$  ( $\sim 0$ ),
- if we split

$$\left( \frac{a_i^{\text{VMD}}}{1 - z m_K^2 / m_V^2} + a_i^{\text{nVMD}} \right) \approx \left[ \left( a_i^{\text{VMD}} + a_i^{\text{nVMD}} \right) + a_i^{\text{VMD}} \frac{m_K^2}{m_V^2} z \right]$$

Then we can determine both terms from expt.

$$a_+^{\text{VMD}} = \frac{m_V^2}{m_K^2} b_+^{\text{exp}} = -1.6 \pm 0.1, \quad a_+^{\text{nVMD}} = a_+^{\text{exp}} - a_+^{\text{VMD}} = 1.0 \pm 0.1$$

- Assuming a short distance relation

Buchalla, Isidori, G.D.

$$(a_S)_{\langle Q_{7V} \rangle} = -(a_+)_{\langle Q_{7V} \rangle}$$

- If this relation is obeyed by the full VMD amplitude

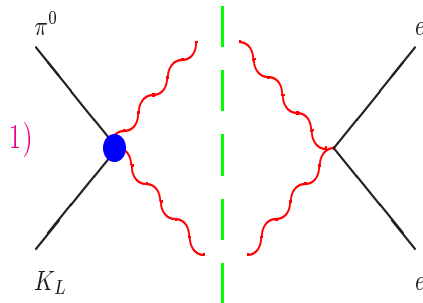
$$(a_S^{\text{VMD}})_{\langle Q_{7V} \rangle} = -a_+^{\text{VMD}} = 1.6 \pm 0.1$$

in good agreement with NA48

$$(|a_S| = 1.08_{-0.21}^{+0.26})$$

$K_L \rightarrow \pi^0 e^+ e^-$  : summary

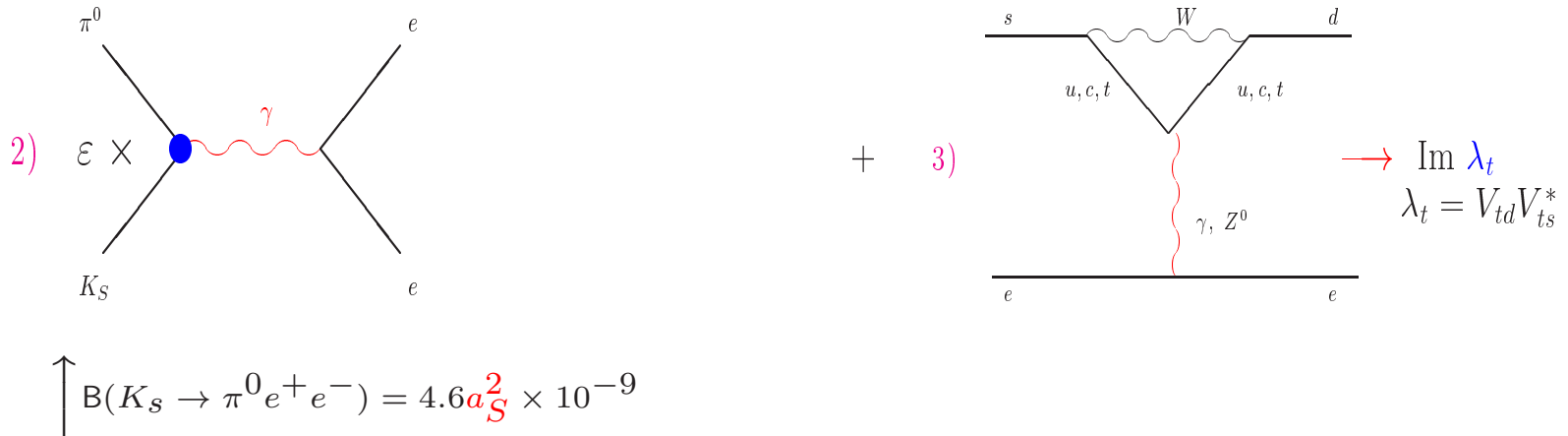
$$\text{Br}(K_L \rightarrow \pi^0 e^+ e^-) \leq 2.8 \cdot 10^{-10} \quad \text{KTeV}$$



CP conserving NA48

$$\text{Br}(K_L \rightarrow \pi^0 e^+ e^-) < 3 \cdot 10^{-12}$$

$V-A \otimes V-A \Rightarrow \langle \pi^0 e^+ e^- | (\bar{s}d)_{V-A} (\bar{e}e)_{V-A} | K_L \rangle$  violates CP



Possible large interference:  $a_S < -0.5$  or  $a_S > 1$ ; short distance probe even for  $a_S$  large

$$|2) + 3)|^2 = \left[ 15.3 a_S^2 - 6.8 \frac{\text{Im} \lambda_t}{10^{-4}} a_S + 2.8 \left( \frac{\text{Im} \lambda_t}{10^{-4}} \right)^2 \right] \cdot 10^{-12}$$

$$[17.2 \pm \quad 9.4 + \quad 4.7] \cdot 10^{-12}$$

## Conclusions

- $K \rightarrow \pi\pi ll$
- $K \rightarrow \pi ll$
- still to discuss  $A_{FB}$  in  $K \rightarrow \pi ll$
- still to discuss time interference in  $K \rightarrow \pi\pi ll$

$$K_S(K_L) \rightarrow \mu \bar{\mu}$$

- $A(K^0 \rightarrow l^+ l^-) = \bar{u}_l (iB + A\gamma_5) v_l$

- if No polarization is measured

$$\Gamma(K_{L,S} \rightarrow \mu^+ \mu^-) = \frac{m_K \beta_l}{8\pi} (|A|^2 + |B|^2) \quad \beta = \sqrt{1 - \frac{4m_\mu^2}{m_K^2}}$$

- For Polarization studies see Peter Heczeg Phys.Rev. D27 (1983) 1512  
LA-UR-82-3262

$$K_L \rightarrow \mu \bar{\mu}$$



$$\frac{\Gamma(K_L \rightarrow \mu \bar{\mu})}{\Gamma(K_L \rightarrow \gamma \gamma)} = |ReA|^2 + |ImA|^2 = (1.238 \pm 0.024) \cdot 10^{-5}$$

$$|ImA|^2 = 27.14 r \implies |Re(A_{SD} + A_{LD})|^2 = (0.98 \pm 0.55) r$$

$r$  kin. factor

Good determination of  $A_{LD} \Rightarrow A_{SD} \Rightarrow$  SM test



## Low energy form factor + matching with VMD to QCD

We use a QCD motivated form factor

G.D. Isidori, Portoles; Isidori, Unterdorfer

$$A(K_L \rightarrow \gamma^*(q_1)\gamma^*(q_2)) = A_{\gamma\gamma}^{\text{exp}} \left[ 1 + \alpha \left( \frac{q_1^2}{q_1^2 - M_V^2} + \frac{q_2^2}{q_2^2 - M_V^2} \right) + \beta \frac{q_1^2 q_2^2}{(q_1^2 - M_V^2)(q_2^2 - M_V^2)} \right]$$

$\alpha$  fixed from  $K_L \rightarrow \gamma\gamma^*$        $\beta$  from  $K_L \rightarrow e^+e^- \mu\bar{\mu}$  (not yet)

Matching with QCD  $q_1^2, q_2^2 \rightarrow \infty$  imposes  $|1 + 2\alpha + \beta| \simeq 0.3$

**Isidori, Unterdorfer**

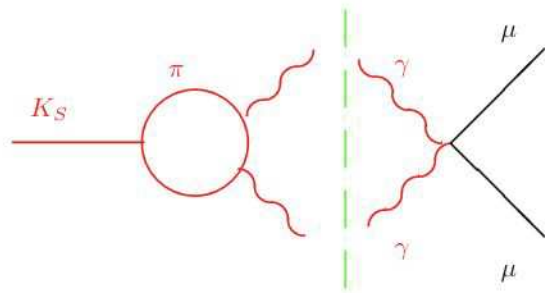
- $|ImA|^2 = 27.14 r \implies |Re(A_{SD} + A_{LD})|^2 = (0.98 \pm 0.55) r$

$r$  kin. factor

- By very accurate study they obtain  $-3.1 < A_{SD} < 1.7 \implies B(K_L \rightarrow \mu\mu)_{SD} < 2.5 \times 10^{-9}$

$K_S \rightarrow \mu \bar{\mu}$  Ecker, Pich; Isidori, Unterdorfer

- $A(K^0 \rightarrow l^+ l^-) = \bar{u}_l (iB + A \gamma_5) v_l$
- $\Gamma(K_{L,S} \rightarrow \mu^+ \mu^-) = \frac{m_K \beta_l}{8\pi} (|A|^2 + |B|^2)$   $\beta = \sqrt{1 - \frac{4m_\mu^2}{m_K^2}}$
- Short distance: **ONLY CP Violating from A**
- SM  $B(K_S \rightarrow \mu \bar{\mu})_{SD} = 1 \times 10^{-5} |\Im(V_{ts}^* V_{td})|^2 \sim 10^{-13}$ ; NP  $\sim 10^{-11}$  allowed;
- LD VERY ACCURATE  $5 \times 10^{-12}$ , error from expt  $B(K_S \rightarrow \gamma \gamma)$
- LHCb  $B(K_S \rightarrow \mu \bar{\mu}) < 11 \times 10^{-9}$  at 95% CL after 40 years



$$K_L(p) \rightarrow \pi^0(p_3) \gamma(q_1) \gamma(q_2)$$

$$\begin{array}{ll} \text{Lorentz + gauge invariance} & \Rightarrow \quad M \sim \begin{array}{cc} A(y, z) & B(y, z) \\ \gamma\gamma & \gamma\gamma \\ J = 0 & \text{D - wave too} \\ F^{\mu\nu} F_{\mu\nu} & F^{\mu\nu} F_{\mu\lambda} \partial_\nu K_L \partial^\lambda \pi^0 \end{array} \end{array}$$

$$y = p \cdot (q_1 - q_2) / m_K^2, \quad z = (q_1 + q_2)^2 / m_K^2$$

$$r_\pi = m_\pi / m_K$$

- $\frac{d^2\Gamma}{dydz} \sim z^2 |A + B|^2 + \left( y^2 - \left( \frac{(1 + r_\pi^2 - z)^2}{4} - r_\pi^2 \right) \right)^2 |B|^2 \quad S, B$
- Different gauge structure  $\Rightarrow B \neq 0$  at  $z \rightarrow 0$  (collinear photons).

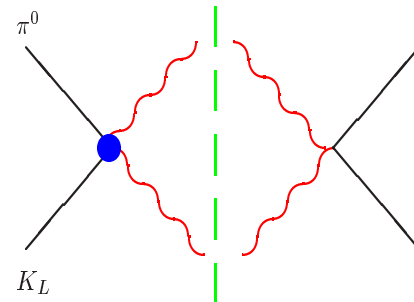
Crucial role in  $K_L \rightarrow \pi^0 e^+ e^-$

A suppressed by  $m_e/m_K$

B is not

Morozumi et al, Flynn Randall

Sehgal Heiliger, Ecker et al., Donoghue et al.



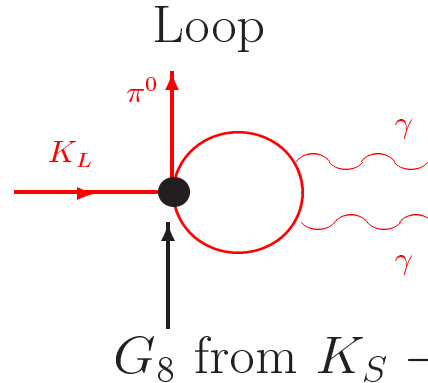
$K_L \rightarrow \pi^0 \gamma \gamma$

Ecker, Pich, de Rafael; Capiello, G.D

- $O(p^4)$

CT

0



only A

But

$$\frac{\Gamma(K_L \rightarrow \pi^0 \gamma \gamma)_{p4}}{\Gamma(K_L \rightarrow \pi^0 \gamma \gamma)_{\text{exp}}} \sim \frac{1}{2.5}$$

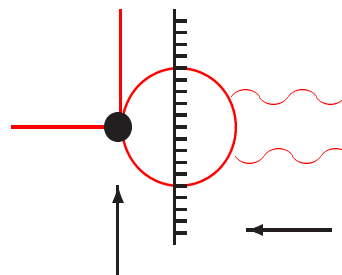
- $O(p^6)$  A, B from:

3 CT's

$$F_{\mu\nu} F^{\mu\alpha} \partial_\alpha K_L \partial^\nu \pi^0$$

$$F^2 \partial K_L \partial \pi^0$$

$$F^2 m_K^2 K_L \pi^0$$



Capiello, G.D., Miragliuolo

Cohen, Ecker, Pich

Full description of unitarity cut

$$A(K \rightarrow 3\pi) = a + b Y + c Y^2 + d X^2$$

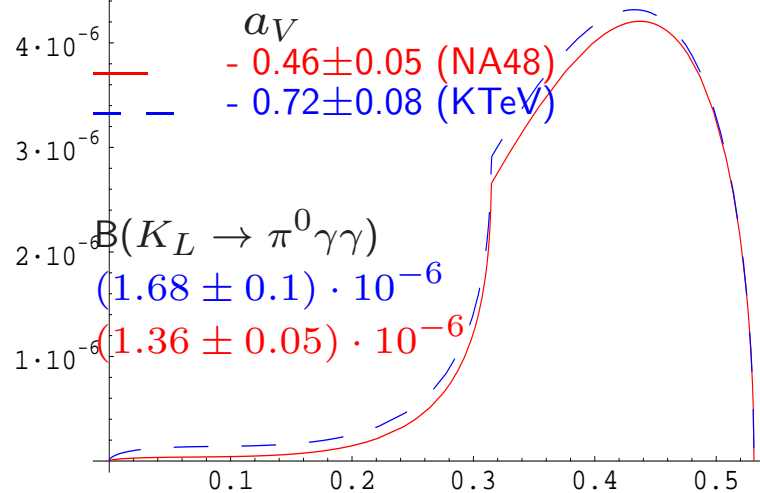
$$A_{CT} = \alpha_1(z - r_\pi^2) + \alpha_2$$

$$B_{CT} = \beta$$

VMD  $\Rightarrow$  1 coupling  $a_V$  ( $\sim -0.6$  G.D., Portoles)  
(Ecker, Pich, de Rafael; Sehgal et al.)

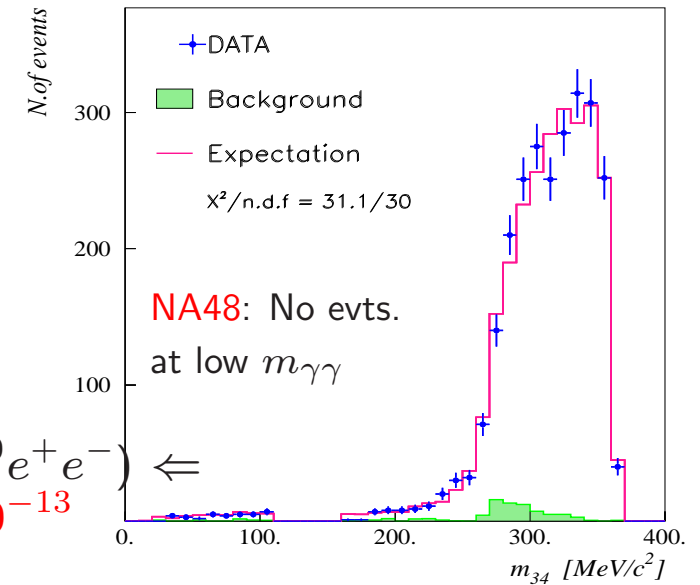
$$\alpha_1 = \frac{\beta}{2} = -\frac{\alpha_2}{3} = -4a_V \sim 2 \quad \text{n.d.a.} \sim 0.2$$

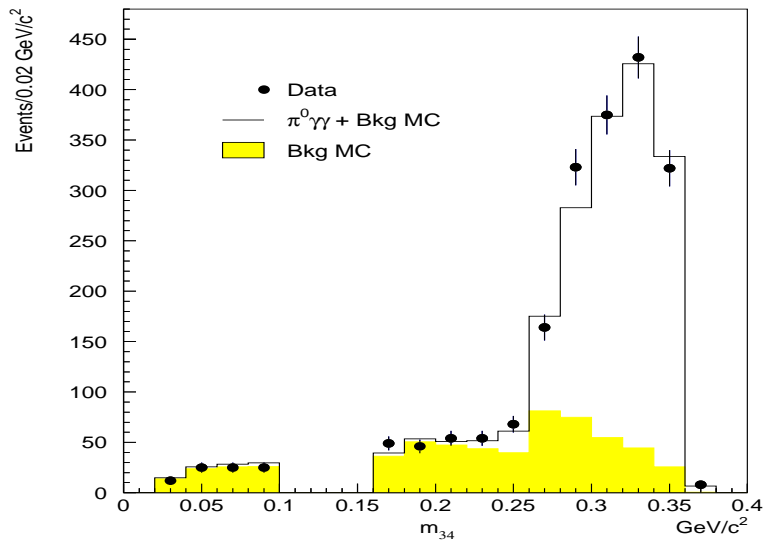
- KTeV and NA48: 1 parameter fit ( $a_V$ ) with all the unitarity corrections



$$B(K_L \rightarrow \pi^0 e^+ e^-) \ll$$

$$< 5 \cdot 10^{-13}$$



$K_L \rightarrow \pi^0 \gamma \gamma$ : KTeV recent data

$$B = (1.29 \pm 0.03 \pm 0.05) \times 10^{-6}$$

$$a_V = -0.31 \pm 0.05 \pm 0.07$$



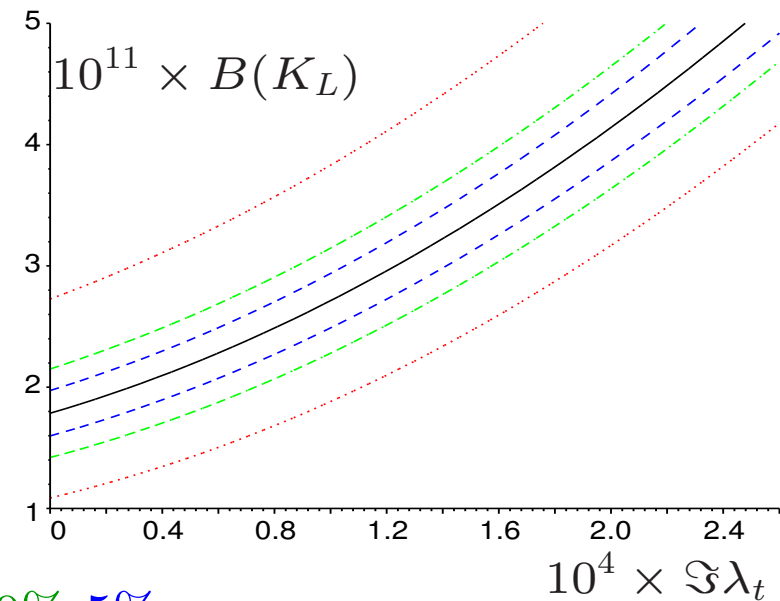
- Having i) **separated** the contribution better suited to comparison with **s.d. (VMD)** and ii) **realized** that this dominates **Theoret.** and **Phenom.(NA48)**  $a_S$
- we believe the **positive interference** of **s.d.**

$$B(K_L \rightarrow \pi^0 e^+ e^-)_{\text{SM}} = (3.1^{+1.2}_{-0.9}) \times 10^{-11} a_S$$

$$\text{KTeV } B(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10} \text{ at } 90\% \text{C.L.}$$

Present error on  $a_S = 1.08, 10\%, 5\%$ , no error

$$K\text{-physics bound: } -1.2 \times 10^{-3} < \Im\lambda_t < 1.0 \times 10^{-3} \text{ at } 90\% \text{C.L.}$$



$$K^+ \rightarrow \pi^+ \gamma \gamma$$

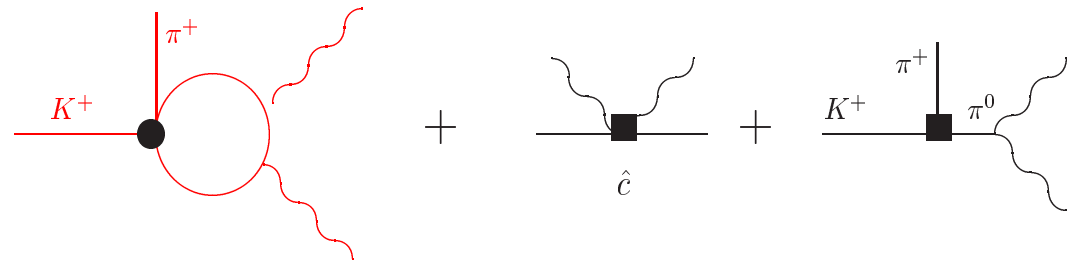
$$\gamma \gamma \quad \text{in} \quad \begin{array}{c} \overbrace{F_{\mu\nu} F^{\mu\nu} \quad F \tilde{F}}^{J=0} \\ P = +1 \quad P = -1 \\ A \quad C \end{array} \quad \begin{array}{c} J=2 \\ B \end{array} + \dots$$

Lorentz + gauge invariance

$$\frac{d^2\Gamma}{dydz} \sim \left[ z^2 (|A + B|^2 + |C|^2) + \left( y^2 - \left( \frac{(1 + r_\pi^2 - z)^2}{4} - r_\pi^2 \right) \right)^2 |B|^2 \right]$$

$$K^+ \rightarrow \pi^+ \gamma \gamma$$

- $O(p^4)$



Ecker, Pich, de Rafael

In factorization  $\hat{c} = \frac{128\pi^2}{3} [3(L_9 + L_{10}) + N_{14} - N_{15} - 2N_{18}] = 2.3(1 - 2k_f)$

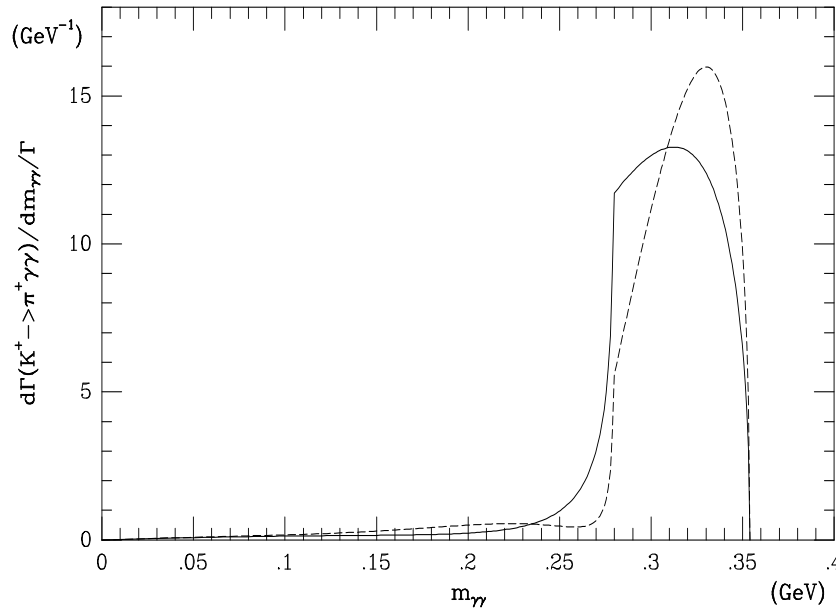
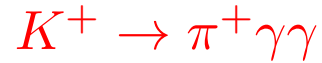
spin-1 contributions (axials) to  $\hat{c}$

- $O(p^6)$

G.D., Portoles 96

Unitarity corrections: 30%-40%

$a_{V^+}$  negligible



—	$\hat{c}$
	0
- - -	-2.3

BNL 787 (96) got 31 events

i) confirm  $O(p^6)$

ii)  $\text{Br} \sim (6 \pm 1.6) \cdot 10^{-7}$

iii)  $\hat{c} = 1.8 \pm 0.6$

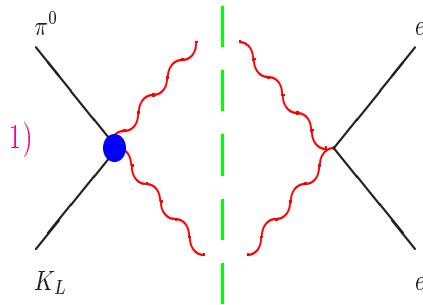
E949 no events at low  $m_{\gamma\gamma}$ :

NA48 published  $K^+ \rightarrow \pi^+ e^+ e^- \gamma$   $\hat{c} = 0.90 \pm 0.45$

NA48 preliminary  $B = (1.07 \pm 0.04 \pm 0.08) \cdot 10^{-6}$ ,  $\hat{c} = 2 \pm 0.25$

$K_L \rightarrow \pi^0 e^+ e^-$  : summary

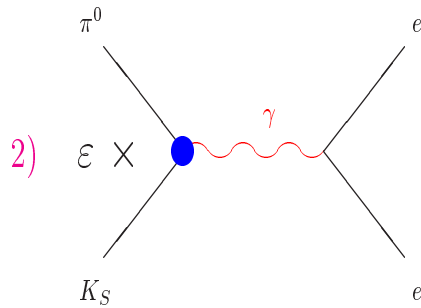
$$\text{Br}(K_L \rightarrow \pi^0 e^+ e^-) \leq 2.8 \cdot 10^{-10} \text{ at 90\% CL} \quad \text{KTeV}$$



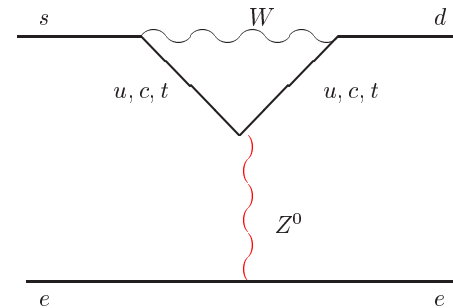
CP conserving NA48

$$\text{Br}(K_L \rightarrow \pi^0 e^+ e^-) < 3 \cdot 10^{-12}$$

$V-A \otimes V-A \Rightarrow \langle \pi^0 e^+ e^- | (\bar{s}d)_{V-A} (\bar{e}e)_{V-A} | K_L \rangle$  violates CP



$$\uparrow \text{B}(K_S \rightarrow \pi^0 e^+ e^-) = 4.6 a_S^2 \times 10^{-9}$$



Possible large interference:  $a_S < -0.5$  or  $a_S > 1$ ; short distance probe even for  $a_S$  large

$$|2) + 3)|^2 = \left[ 15.3 a_S^2 - 6.8 \frac{\text{Im} \lambda_t}{10^{-4}} a_S + 2.8 \left( \frac{\text{Im} \lambda_t}{10^{-4}} \right)^2 \right] \cdot 10^{-12}$$

$$[17.7 \pm \quad 9.5 + \quad 4.7] \cdot 10^{-12}$$

## Conclusions

- CP conserving contribution in  $K_L \rightarrow \pi^0 ee$  is small: confirmed also from  $K^+ \rightarrow \pi^+ \gamma \gamma$  by NA48/2 - NA62
- $K^+ \rightarrow \pi^+ \pi^0 ee$  interesting new channel , see also  $K^+ \rightarrow \pi^+ \pi^0 \mu \mu$
- LHCb entering in the scene, 40 years step, see also other  $K_S$  channels

## How to extract SD from $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$

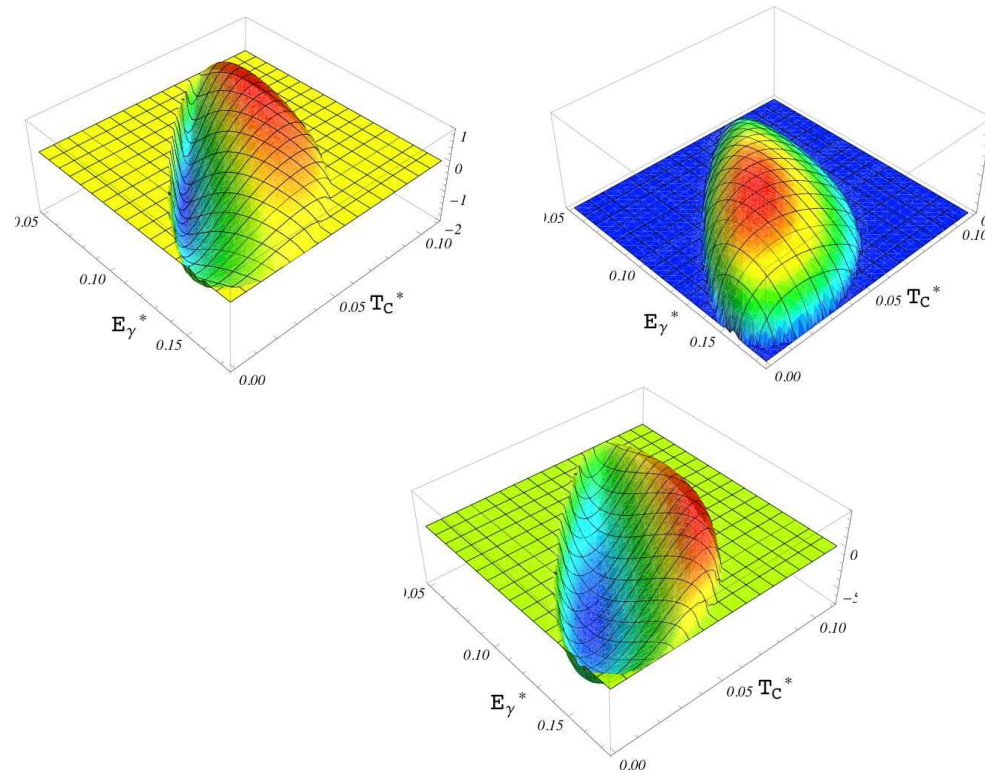


Figure 1: Dalitz plot for the contributions to  $A_P^{(S)}$  (in arbitrary units) at  $q^2 = (50 \text{ MeV})^2$ .



## Novel CP violation contributions (compared to $A_{CP}(K^+ \rightarrow \pi^+ \pi^0 \gamma)$ )

$$A_{CP} = \frac{\Gamma(K^+ \rightarrow \pi^+ \pi^0 e^+ e^-) - \Gamma(K^- \rightarrow \pi^- \pi^0 e^+ e^-)}{\Gamma(K^+ \rightarrow \pi^+ \pi^0 e^+ e^-) + \Gamma(K^- \rightarrow \pi^- \pi^0 e^+ e^-)}$$

